FLOW OF NON-NEWTONIAN FLUID THROUGH POROUS MEDIUM

BY

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DISSERTATION

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In Partial Fulfilment of the Requirements

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Bachelor of Engineering (Hons)

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Approved:

Professor Dr Noaman El Khatib

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UNIVERSITI TEKNOLOGI PETRONAS

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or persons.

KHAIRUL ASUAD AB GANI

ABSTRACT.

This is the final report done on the chosen topic, which is **Flow of Non-Newtonian Fluids through Porous Media.** The objective of the project is to study the behaviour of non-Newtonian Fluid behaviour when flowing through porous medium. The core objective of the project is to study the behaviour of different non-Newtonian Fluid samples when flowing through porous medium. The challenge faced is to understand the basic concept of non-Newtonian fluid. As we know, there's a lot of different concept and different perspective for non-Newtonian fluid.. Furthermore, since the non-Newtonian fluid does not obey the Newtonian fluid behaviour, it is impossible to predict the flow of the non-Newtonian fluid inside porous medium. This is because the flow of non-Newtonian fluid is not described by a single constant value of velocity. Because of that, Lab testing will be done for the non-Newtonian fluid sample to study the behaviour. The non-Newtonian fluid used will be different polymer samples and from the lab experiment, the measurement of n and K value will be determined by injecting different polymer sample through porous medium. Further research has been done by the student in order to adhere the topic

Figure 1.2: The classes of the time-independent fluids presented in a graph of stress against strain rate in shear flow.

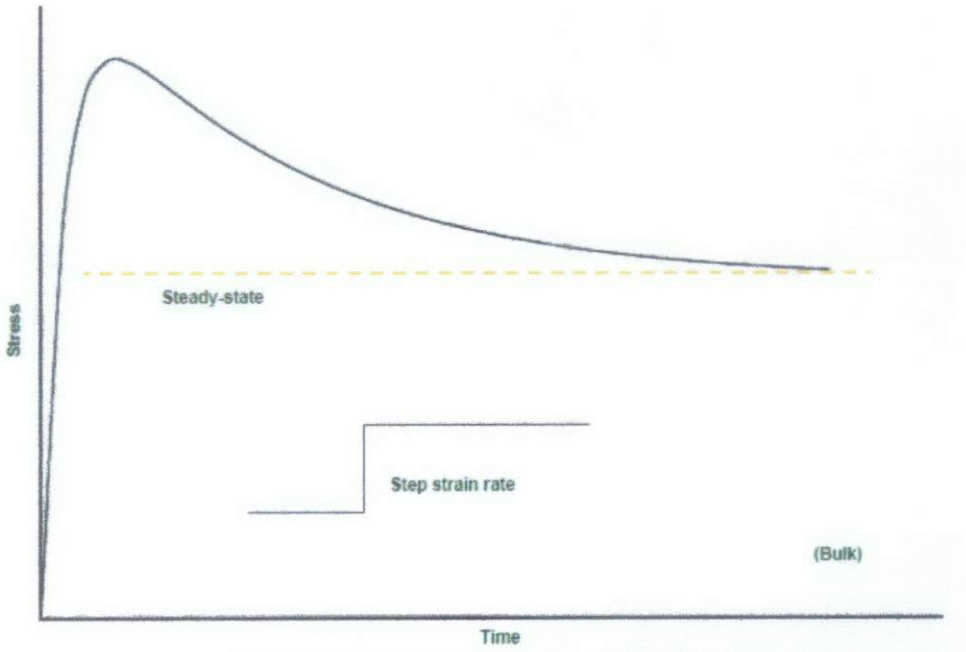


Figure 1.3: Typical time-dependence behavior of viscoelastic fluids due to delayed response and relaxation following a step increase in strain rate.

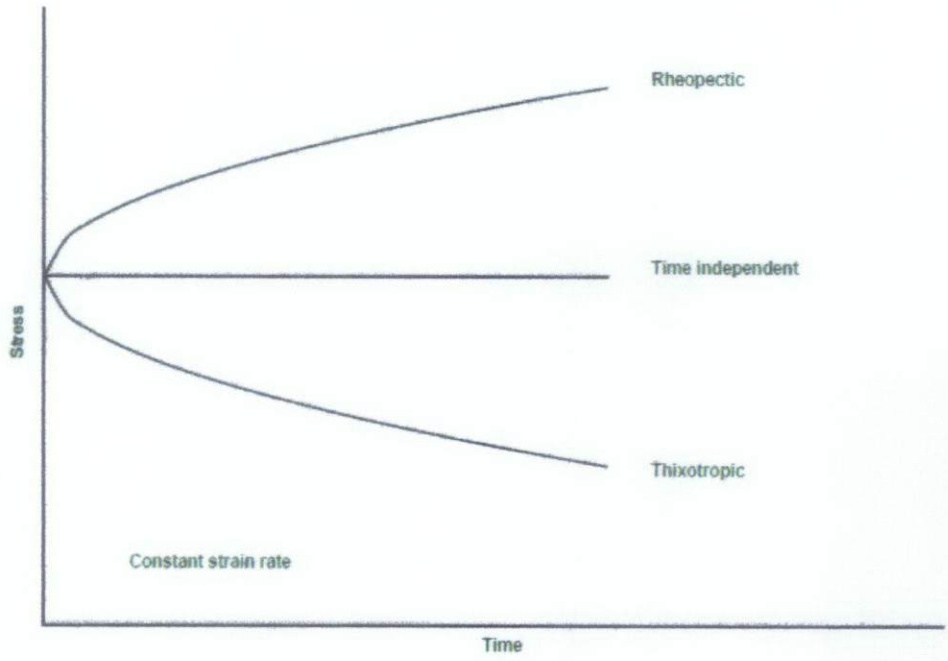


Figure 1.4: The two classes of time-dependent fluids compared to the time independent presented in a generic graph of stress against time.

PROBLEM STATEMENT

Various researches had been done to study the flow behaviour of non-Newtonian Fluid in porous medium. Since many of the fluid used in petroleum industry to treat or stimulate the well is made of non-Newtonian fluid, they are complex, chemically and can react well with porous medium in formation such as sand formation (sandstone) and carbonate formation (limestone). Since these fluids that are to be pumped inside the reservoir through this porous formation, it is necessary to understand the flow behaviour of the fluid. Since these porous medium show inhomogeneities in their complex structure, a simple mathematical model and lab works are needed to be done in order to acquire an idea of the fluid behaviour inside the reservoir. If the flow behaviour can be predicted, useful information can be obtain to help improve the well stimulation process, enhanced oil recovery (EOR) and many more. Therefore this project aims is to study the flow behaviour of non-Newtonian fluid inside porous medium also to aid in further study on this matter.

1.3 OBJECTIVE AND SCOPE OF STUDY

The main objectives of this research are:

- To study the flow behaviour of non-Newtonian fluid in porous medium
- To analyze how can the study of non-Newtonian fluid flow in porous medium can help enhance oil recovery
- To determine the application of non-Newtonian fluid flow in the petroleum industry
- To understand the rheological properties of non-Newtonian fluid and the effect it have on the porous medium
- To establish the relationship between stress and strain rate in non-Newtonian fluid

The scope of work for this project is to investigate the flowability and workability of Non-Newtonian fluid inside the porous medium. Several lab works will be done to simulate the performance of non-Newtonian fluid in downhole formation where it will be subjected to porosity and permeability.

1.4 The Relevancy of the Project

The non-Newtonian fluid plays a major role in enhancing oil recovery (EOR). Hence, most of the reservoir fluids are made of non-Newtonian fluids. By understanding the non-Newtonian fluids basic concept and application, not only it can improve the oil recovery but also the whole process of from drilling to productions. Thus with better understanding regarding the behaviour of non-Newtonian fluid flow inside the porous medium, it helps us to determine and estimate the flow behaviour of the fluid and minimize the cost for recovery and production. Since the main target of the oil company is to maximise production and minimise expenditure, shows us that this project is relevant especially in the industry of oil and gas.

1.5 Feasibility of the Project within the Scope and Time frame

Throughout this semester, literature review on rheology of non-Newtonian fluids will be conducted as many as possible. It will cover more on equations involved, rheological models, theory behind it and all related applications. Since only work on reviewing the topic, it is feasible enough to complete the first phase of this project within this semester. The second phase of this project is expected to begin by next semester. The main activity is to conduct experiment regarding the topic. After studying on the flow of non- Newtonian fluids through porous medium for a semester, the feasibility to run the experiment is undeniable.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter review some related issues regarding non-Newtonian fluid. Non-Newtonian fluid in its simplest explanation is fluid which does not obey the Newtonian fluid law. The non-Newtonian fluid can be easily found in and are widely use in our daily life such as ketchup, oil, and paint.

There are 3 major types of non-Newtonian Fluid which is;

1. Time Independent Fluid
2. Time Dependent Fluid
3. Viscoelastic Fluid

2.11 *Time Independent Fluid;*

Shear rate dependence is one of the most important and defining characteristics of non-Newtonian fluids in general and time-independent fluids in particular. There are two types of time independent fluid model which is;

1. Shear-thinning or pseudoplastic which is the effect where viscosity of the fluid decreases with increasing rate of shear stress. Materials that exhibit shear thinning are called **pseudoplastic**. This property is found in certain complex solutions, such as lava, ketchup, and whipped cream. It is also a common property of polymer solutions and molten polymers. Pseudoplasticity can be demonstrated by the manner in which squeezing a bottle of ketchup, a Bingham plastic, causes the contents to undergo a change in viscosity. The force causes it to go from being thick like honey to flowing like water. Unlike a thixotropic fluid, shear thinning fluid viscosity decreases with ***increasing shear rate***, while thixotropic fluid viscosity decreases *over* ***time at a constant shear rate***.
2. Shear-thickening or dilatants is the effect in which viscosity of the fluid increases with the rate of shear applied on the fluid. This is due to when closely packed particles are combined with enough liquid to fill the gaps between them. At low velocities, the liquid acts as a lubricant, and the dilatant flows easily. At higher

velocities, the liquid is unable to fill the gaps created between particles, and friction greatly increases, causing an increase in viscosity.

If the fluid sustains initial stress without flowing, it is called a yield-stress fluid. Almost all polymer solutions that exhibit a shear rate dependent viscosity are shear-thinning, with relatively few polymer solutions demonstrating dilatant behavior. Moreover, in most known cases of shear-thickening there is a region of shear-thinning at lower shear rates.

There are 4 fluid models that are widely used to models the time-independent group of the non-Newtonian Fluid which is;

1. Ostwald-de Waele Model (Power Law Model)

This mathematical model is useful due to the simplicity of it. The model is given by the relation of;

$$\mu_{\text{eff}} = K\left(\frac{\partial u}{\partial y}\right)^{n-1}$$

Where K= Consistency Factor, $\frac{\delta u}{\delta y}$ @ sometimes we use $\dot{\gamma}$ as the shear rate, n is the flow behaviour index and μ is the viscosity of the fluid. In Figure 2.1a (below) the bulk rheology of this model for the shear-thinning case is presented as viscosity vs. Shear rate on log-log scales. The Power Law fluid can be subdivided into 3 different types of groups which is;

N	Type of Fluid
<1	Pseudoplastic Fluid
1	Newtonian Fluid
>1	Dilatant Fluid (less common)

Table 2: Fluid behaviour number and type of fluid

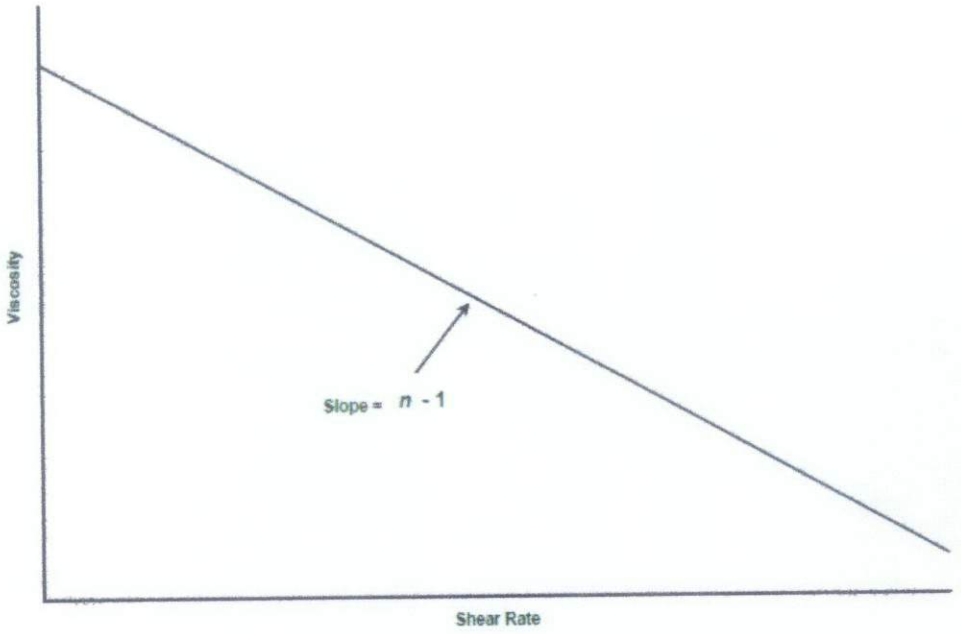


Figure 2.1a: The bulk rheology of a power-law fluid on logarithmic scales for finite shear rate $(\frac{\delta u}{\delta y} > 0)$

2. Ellis Model

This model describes the time-independent shear thinning non-yield stress fluid. It is used as a substitute for power law fluid and matching experimental measurements better compared to power law fluid. According to the model, the viscosity of the fluid μ is given by;

$$\mu = \frac{\mu_o}{1 + \left(\frac{\tau}{\tau_{1/2}}\right)^{\alpha-1}}$$

Where μ_o is the low shear viscosity, τ is the shear stress, $\tau_{\frac{1}{2}}$ is the shear stress at which $\mu = \frac{\mu_o}{2}$ and $\alpha = \frac{1}{n}$. In Figure 2.1b below is the bulk rheology graph of viscosity versus shear rate at logarithmic scales.

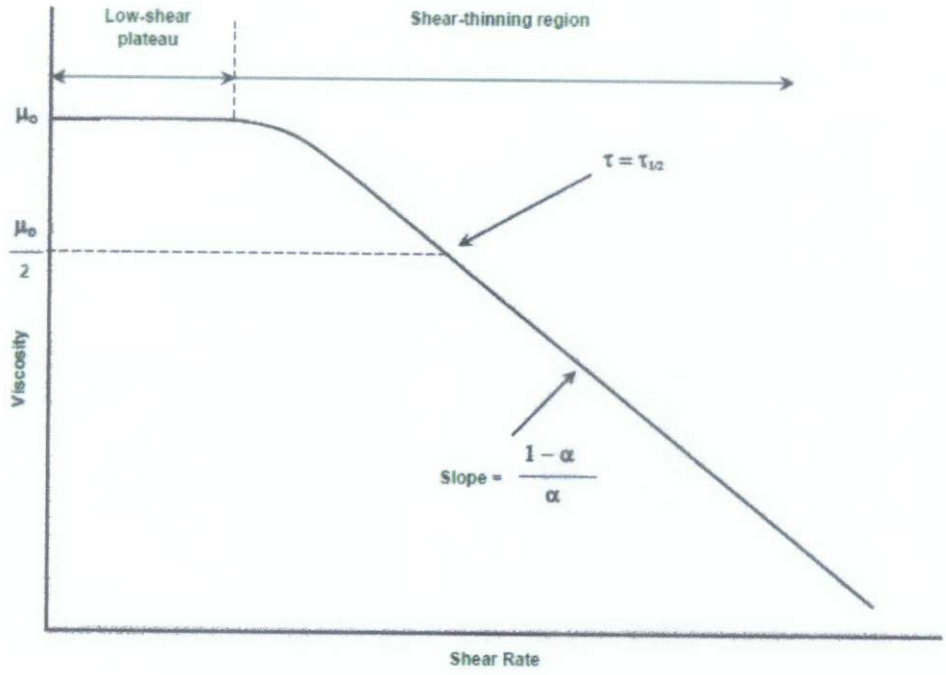


Figure 2.1b: The Bulk Rheology of an Ellis Fluid on logarithmic scale for finite shear rate $(\frac{\delta u}{\delta y} > 0)$.

3. Carreau Model

This model describes the shear-thinning fluids with no yield stress. This model is used when there are significant deviations from the power-law model at very high and very low shear rates. The relation of the model is;

$$\mu = \mu_\infty + \frac{\mu_o - \mu_\infty}{[1 + (\dot{\gamma} t_c)^2]^{\frac{1-n}{2}}}$$

Where where μ is the fluid viscosity, μ_∞ is the viscosity at infnite shear rate, μo is the viscosity at zero shear rate, ý is the shear rate, tc is a characteristic time and n is the flow behavior index. Below (figure 2.1c) is the graph demonstrating bulk rheology of the model;

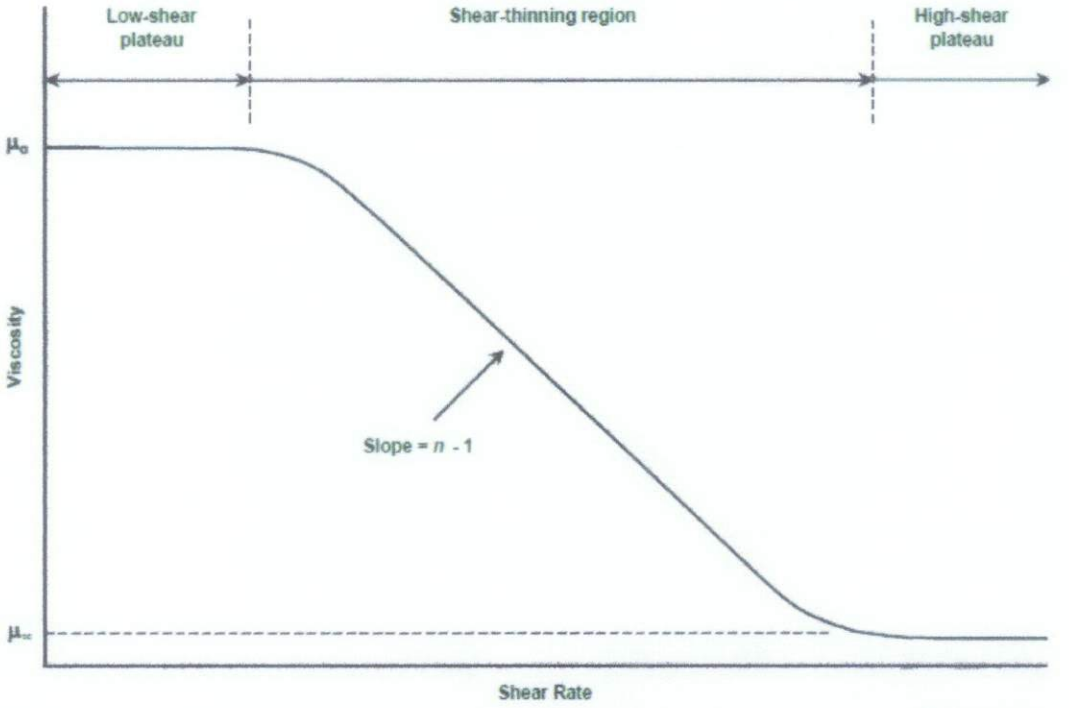


Figure 2.1c: The Bulk rheology of a Carreau fluid in logarithmic scals for finite shear rates ($\dot{\gamma}$>1).

4. Herschel-Bulkley Model

This is a simple model with 3 parameters. Eventhough the model is simple; it can describe all main classes of time-independent non-Newtonian fluids. The relation of the model is;

$$\tau = \tau_o + C\dot{\gamma}^n (\tau > \tau_o)$$

Where τ is the shear stress, τ_o is the yield stress above which the fluid starts flowing, C is the Consistency factor, $\dot{\gamma}$ is the shear rate and n is the flow behaviour index. When $\tau_o = 0$, the Herschel-Bulkley model will be rediced to power law and when $\tau_o = 1$ it will become Bigham plastic model.

There are 6 main classes to this model which is;

No.	Classes	Condition
1	Shear-thinning (pseudoplastic)	[$\tau_o = 0; n < 1$]
2	Newtonian	[$\tau_o = 0; n = 1$]
3	Shear-thickening (dilatants)	[$\tau_o = 0; n > 1$]
4	Shear-thinning with yield-stress	[$\tau_o > 0; n < 1$]
5	Bigham Plastic	[$\tau_o > 0; n = 1$]
6	Shear-thickening with yield-stress	[$\tau_o > 0; n > 1$]

Table 3: Classes of Herschel-Bulkley Model

2.12 *Time Dependent Fluid.*

There are two main types of time-dependent fluid which is;

a) Thixotropic (work softening) which is the property of certain gels or fluids that are thick (viscous) under normal conditions, but flow (become thin, less viscous) over time when shaken, agitated, or otherwise stressed. In more technical language: some non-Newtonian pseudoplastic fluids show a time-dependent change in viscosity; the longer the fluid undergoes shear stress, the lower its viscosity. A thixotropic fluid is a fluid which takes a finite time to attain equilibrium viscosity when introduced to a step change in shear rate. However, this is not a universal definition; the term is sometimes applied to pseudoplastic fluids without a viscosity/time component. Many gels and colloids are thixotropic materials, exhibiting a stable form at rest but becoming fluid when agitated.

b) Rheopectic (work hardening) which is the rare property of some non-Newtonian fluids to show a time-dependent change in viscosity; the longer the fluid undergoes shearing force, the higher its viscosity. Rheopectic fluids, such as some lubricants, thicken or solidify when shaken. The opposite type of behaviour, in which fluids become less viscous the longer they undergo shear, is called thixotropy and is much more common. Examples of rheopectic fluids include gypsum pastes and printers inks.

Both of these time dependent fluid are depending upon the change in stress applied with time at a given strain rate and constant temperature.

There are 2 models of the group that are widely used which is;

1. Godfrey Model

   This model suggested that at specific shear rate, the time dependence of thixotropic fluid can be defined by such relation;

$$\mu(t) = \mu_i - \Delta\mu'(1 - e^{-t/\lambda'}) - \Delta\mu''(1 - e^{-t/\lambda''})$$

   Which μ(t) is the time dependent viscosity, μ_i is the viscosity at the commencement of deformation, Δμ′ and Δμ″ are the viscosity deficits associated with the decay time constant λ' and λ''respectively and t is the time of shearing. The initial viscosity shows the maximum value while the viscosity deficits specify the reduction associate with time constants. The time constant define the time scales of the process under examination.

2. Stretched Exponential Model

$$\mu(t) = \mu_i + (\mu_{inf} - \mu_i)(1 - e^{-(t/\lambda_s)^c})$$

   This model describes both thixotropic and rheopetic rheology. From the equation above, μ(t) is the time dependent viscosity, μ_i is the viscosity at the commencement of deformation, $\mu_{inf}$is the equilibrium viscosity at infinite time, t is the time of deformation λ_s is the time constant and c is the dimensionless constant which in the simplest case is unity.

2.13 *Viscoelastic Fluid*

Most of the polymetric fluid shows a strong viscoelastic effects which includes shear-thinning, extension-thickening, normal stresses and time dependent rheology. For the time being, there's no theory that can adequately describe all the observed properties of viscoelastic fluid in a different type of flow. There are two types of viscoelastic fluid whic is;

Linear Viscoelasticity

Is the field of rheology that study the viscoelastic materials under very small strain or deformation where the displacement gradients are very small and the flow regime can be described by a linear relationship between stress and strain rate. By principle, the strain has to be small enough so that the structure of the material remains undisturbed by the ow history. If the strain rate is small enough, deviation from linear viscoelasticity may not occur at all. The equations of linear viscoelasticity are not valid for deformations of arbitrary magnitude and rate because they violate the principle of frame invariance. Hence, viscoelastic constitutive equations are valid in general for any strain rate as long as the total strain remains small. Nevertheless, the higher the strain rate the shorter the time at which the critical strain for departure from linear regime is reached. In addition, the linear viscoelastic models have several limitations. For example, they cannot describe strain rate dependence of viscosity or normal stress phenomena since these are nonlinear effects. Due to the restriction to a very smallest deformation, the linear models may be more appropriate for the description of viscoelastic solids rather than viscoelastic fluids. Despite the limitations of the linear viscoelastic models and despite being of less interest to the study of flow where the materialis usually subject to large deformation, they are very important in the study of viscoelasticity for some reasons;

a. They are used to characterised the behaviour of viscoelastic material at small deformation
b. They serve as a motivation and starting point for developing nonlinear models
c. They are used for analyzing experimental data obtained in small deformation experiments and for interpreting important viscoelastc phenomena qualitatively

Non-Linear Viscoelasticity

is the study of material under large deformation and is the subject of main interest to the study of flow for viscoelastic fluid. The non-linear viscoelastic constitutive equation is complex that a very few flow problems can be solved analytically. From the research done, apparently there is no differential or integral constitutive equation general enough to explain the observe behaviour of polymeric system which undergoes a large deformation but yet still simple enough to provide a basis for engineering design procedures.

Various types of non-Newtonian fluid have been developed for specialist application and the most common ones in oil and gas field are for treating and stimulating the reservoir such as for enhancing oil recovery and improve well performance in production. There are a lot of non-Newtonian fluid model but first we have to know the basic of the Newtonian fluid which can be derived from the Darcy Equation. This is because good mathematical models for the transport process are needed. In the past, this was based on continuum models.

2.2 Darcy's Law & Continuum Model.

In continuum models, the porous medium are said to be continuum. First we need to assume that any such medium when dry (containing no fluid in its pores) will consist of one continuous region of solid, the matrix, and regions of void, the pores are continuously connected (continuum).

Darcy Law.

The starting point of the continuum model is the Darcy's law. Darcy's law in its original form states that a linear Newtonian model is based on the relation between the gradient of pore fluid pressure to pore fluid flux within a porous medium. Apparently, this law is the simplest way to describe the fluid flow in porous medium. This law is applicable to laminar flow at low Reynold's Number (any flow with Reynold's Number ≤ 1 are laminar flow. Darcy's law is written as;

$$u = -\left(\frac{k}{\mu}\right)(\nabla p - \rho g) = \left(-\frac{k}{\mu}\right)\nabla \tilde{p}$$

Where u=mean velocity of the pore fluid, p=mean absolute pressure of the pore fluid, ρ *and* μ are density and viscosity of the fluid, g=gravitational force and k=is the permeability of the matrix. The assumptions used for this model are;

1. The fluid is Newtonian
2. The matrix used is isotropic (uniform in all direction)
3. The flow is laminar

Darcy Law's also neglects the boundary effect and heat transfer. Thus, in the original Darcy model, it neglects all effects except cause by the viscous Newtonian effects. Therefore this law is only valid for laminar, isothermal and purely viscous, incompressible Newtonian flow. The advantages of continuum model are;

1. Having a closed form constitutive equation that describes the phenomenon of highly complex of flow through porous media using simple compact terms
2. Easy to use without any computational cost

But the continuum model suffers from some limitation since its ignoring the physics of flow at pore level. In non-Newtonian flow, several pertinent modifications have been done to the continuum models to suit the non-Newtonian behaviour. However, attempts to find a suitable definition for effective viscosity to determine the dimension and physical significance of Newtonian viscosity weather its theoretical and empirical have limited success in predicting the behaviour of non-Newtonian fluid in porous medium.

For extended media, naturally we supposed that $\boldsymbol{u}$, p and k can become functions of position x and time t. If both fluid and matrix are incompressible—an approximation that will be adopted for simplicity throughout this account—then the mass conservation law becomes

$$\nabla \cdot \boldsymbol{u} = 0$$

And the field equation for pressure is;

$$\nabla \ln \frac{k}{\mu} \cdot \nabla \tilde{p} + \nabla^2 \tilde{p} = 0$$

If the porous medium and the pore fluid are homogeneous, and this was often assumed in early work, then the reduced pressure $\tilde{p}$ obeys the harmonic equation. Boundary conditions on either pressure or velocity lead to well-posed problems, which can be solved relatively easily. It is known that real porous media are not homogeneous, though in practice the spatial variation of $k(x)$ is at best inferred from a limited series of tests on small samples of the porous medium in question. It is, therefore, conventional to regard $k(x)$ as a random function of position, describable by a limited number of numerical parameters defining its statistics Solutions now become statistical (probabilistic) rather than exact, and the subtleties of predicting consequences (interpreting results) for given boundary conditions have led to a large and growing literature. Reservoirs are normally highly stratified and so the scalar k has to be replaced by a tensor permeability

For Non-Newtonian Fluid

Darcy Law has been modified in many ways to accommodate more complicated phenomena such as Non-Newtonian fluid and multi-phase flow. Various generalization has been derived using homogenization or volume averaging method.

Here are the three most commonly used continuum models which is

1. Darcy Model

$$\frac{\Delta P}{L} = \frac{\mu q}{K}$$

2. Blake-Kozeny-Carman Model (BKC)

   The **Kozeny–Carman equation** is a relation used in the field of fluid dynamics to calculate the pressure drop of a fluid flowing through a packed bed of solids. It is named after Josef Kozeny and Philip C. Carman. The equation is only valid for laminar flow.

$$\frac{\Delta P}{L} = \frac{72C'\mu q(1-\epsilon)^2}{D_p^2\epsilon^3}$$

   Where Δp is the pressure drop, L is the total height of the bed, $\bar{V}_0$ is the superficial or "empty-tower" velocity, μ is the viscosity of the fluid, ε is the porosity of the bed, Φ_s is the sphericity of the particles in the packed bed, and D_p is the diameter of the related spherical particle. This equation holds for flow through packed beds with particle Reynolds numbers up to approximately 1.0, after which point frequent shifting of flow channels in the bed causes considerable kinetic energy losses. Some forms in this family envisage the bed as a bundle of straight tubes of complicated cross-section with an average hydraulic radius. Other forms depict the porous material as a bundle of tortuous tangled capillary tubes for which the equation of Navier-Stokes is applicable. The effect of tortuosity on the average velocity in the flow channels gives more accurate portrayal of non-Newtonian flow in real beds This equation can be expressed as flow is proportional to the pressure drop and inversely proportional to the fluid viscosity, which is known as Darcy's law.

3. Ergun Model

$$\frac{\Delta P}{L} = \frac{150\mu q}{D_n^2}\frac{(1-\epsilon)^2}{\epsilon^3} + \frac{1.75\rho q^2}{D_p}\frac{(1-\epsilon)}{\epsilon^3}$$

This is a semi-empirical relation that links the pressure drop along a packed bed to the superficial velocity. In this equation, Ergun concluded that the pressure drop across a packed bed depended on the fluid flow rate, viscosity and density, the shape, surface and size of the particles, and the closeness of packing. His equation combines the *Carmen-Korenzy Equation*, valid for laminar flow, and the *Burke-Plumber Equation*, valid for turbulent flow. This equation is widely use to simulates the flow through porous media and models the fluid property. Compared to Kozeny–Carman equation which contains viscous term, this equation contains both inertial and viscous term. This helps makes the Ergun equation able to reach flow regimes that are not accessible to Darcy or BKC. Deriving the Ergun equation are based on a superposition of two asymptotic solutions, one for very low and one for very high Reynolds number flow. The lower limit, namely the BKC equation, is quantitatively attributable to a fully developed laminar flow in a three-dimensional porous structure, while in the higher limit the empirical Burke-Plummer equation for turbulent flow is applied.

2.3 Capillary Bundle Models

In the capillary bundle tube models, the porous mediums are simplified into a bundle of capillary tubes. This is because in practise, the actual pore networks that actually exist in the porous medium are too complex. Hence it is simplified as a collection of tubes. The simplest forms of the model are identical, straight, cylindrical and oriented in a single direction.

Darcy's law and Poiseulle's law are used to show the relationship for the permeability of the model;

$$K = \frac{\epsilon R^2}{8}$$

Where K and ϵ are permeability and porosity of the bundle and R= radius of the tube used. The equation is derived from the Darcy's equation and Poiseulle's Law equation of state.

The Darcy Equation used are;

$$\frac{\Delta P}{L} = \frac{\mu q}{K}$$

And the equation for Poiseulle's Law is;

$$\Delta P = \frac{8\mu LQ}{\pi r^4}$$

By eliminating the similar properties such as viscosity μ, L, and Q, we managed to get the equation as the above equation but in different measure which is;

$$K = \frac{\pi r^4}{8}$$

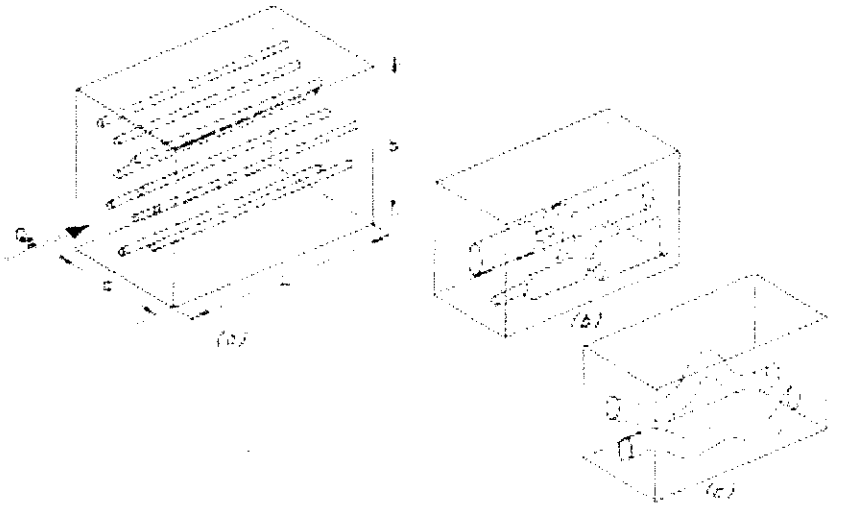


Figure 2.1; Simulation of bundle capillary tube

Beginning with the simplest useful model, consider a collection of capillary tubes or varying diameters placed into an open body of water. The water will rise to different heights depending on the tube radii. At any elevation, the percentage of the cross sectional area of all of the tubes that are water-filled defines the saturation.

However there is certain limitation to this model which is;

1. The capillaries do not vary in diameter along their length.
2. The pores are all perfectly connected vertically and not connected horizontally.
3. The model cannot represent an appropriate residual saturation

2.3 Numerical Methods

In numerical methods, to solve the flow field numerical methods, such as finite volume and finite difference, usually in conjunction with computational implementation are used. The advantage of these methods is that they use the most direct way to describe the physical situation and the closest to full analytical solution. Thus, these method also capable at least, to deal with time-dependent transient situations. The disadvantage is they need a detailed pore space description. Moreover, they are very complex and hard to implement with a huge computational cost and serious convergence difficulties. Because of that, the flow processes and porous media that are currently within the reach of numerical investigation are the simplest ones. These methods are also used for investigating the flow in capillaries with various geometries.

2.4 Pore Scale Network Modelling

The pore scale network modelling is the simplistic approach that simulates the flow in ideal situation. The strategy is by using the bulk rheology of fluid and the void space in the porous medium as an input to the model. The simulation in a network starts with a single capillary followed by networks of capillary which can be determine from set of equation that represents the capillaries and satisfying mass conservation which need to be solved simultaneously to find the physical quantities. The flow in a single capillary can be described as;

$$Q=G'\Delta P$$

Where Q=volumetric flow rate, G' is the flow conductance and ΔP is the pressure drop. In this model, pore space is represented by a lattice of pores connected by throats. Then, once the flow behaviour in a single, the overall flow in the network can be computed or estimated weather by simulation or calculation. I have decided to proceed on Ellis and Herschel–Bulkley models, since most of the researchers are focusing on this models. The advantage of studying Ellis fluids is the availability of an analytical expression for the volumetric flow rate in a single throat. Moreover, unlike the power-law model it demonstrates a realistic viscous behavior at low-shear. The advantage of using the Herschel–Bulkley model is that, besides

the availability of an analytical expression for the flow rate, it can model all the main classes of the time-independent flow behavior including shear-thickening and yield-stress fluids.

Ellis Model

This model describes time independent shear-thinning yield-free non-Newtonian fluids. Its distinctive feature is the low-shear Newtonian plateau without a high-shear one. According to this model, the fluid viscosity μ is given by;

$$\mu = \frac{\mu_0}{1 + \left(\frac{\tau}{\tau_{1/2}}\right)^{\alpha-1}}$$

Where μ_0 is the low-shear viscosity, τ is the shear stress, $\tau_{1/2}$ is the shear stress at which $\mu = \mu_0/2$ and α is an indicial parameter.

Herschel–Bulkley

This model has three parameters and can describe Newtonian and a large group of time independent non-Newtonian fluids. It is given by;

$$\tau = \tau_0 + C\dot{\gamma}^n (\tau > \tau_0)$$

Where τ is the shear stress, τ_0 is the yield stress above which the fluid starts flowing, C is the Consistency factor, $\dot{\gamma}$ is the shear rate and n is the flow behaviour index. There are six main classes to this model;

1. shear thinning (n<1.0)
2. shear thickening (n>1.0) and
3. neither(n=1.0); each either with yield stress (τ_0>0) or without yield stress (τ_0>0)

For Herschel–Bulkley fluids, the volumetric flow rate in a circular cylindrical tube is given by;

$$Q = \frac{8\pi}{C^{\frac{1}{n}}}\left(\frac{L}{\Delta P}\right)^{\frac{1}{n}} (\tau_w - \tau_0)^{1+\frac{1}{n}} \quad X \quad \left[\frac{(\tau_w - \tau_0)^2}{3 + 1/n} + \frac{2\tau_0(\tau_w - \tau_0)}{2 + 1/n} + \frac{\tau_0^2}{1 + 1/n}\right] (\tau_w > \tau_0) \quad \text{a)}$$

where τ_0, C and n are the Herschel–Bulkley parameters, L is the tube length, ΔP is the pressure drop across the tube and τ_w is the shear stress at the tube wall (= ΔP R/2L). For

yield-stress fluids, the threshold pressure drop, ΔP_{th}, above which the flow in a single tube starts, is;

$$\Delta P_{th} = \frac{2L\tau_o}{R}. \qquad \text{(b)}$$

The fact that for a Herschel– Bulkley fluid with a yield stress, the flow occurs when Q>0 where Q is given by Equation (a). The assumptions made are τ_o, R, L, C, ΔP, n>0, it is straightforward to show that the condition Q>0 is satisfied if $(\tau_w - \tau_o)>0$, that is:

$$\tau_w = \frac{\Delta PR}{2L} > \tau_o \qquad \text{©}$$

which produces Equation (b). Alternatively, the flow occurs when the shear stress at the tube wall exceeds the yield stress, i.e. $\tau_w > \tau_o$, which leads to the same condition.

In addition, to model the flow in porous media of complex fluids that have time dependency in a dynamic sense due to thixotropic or elastic nature, there are three major difficulties;

- The difficulty of tracking the fluid elements in the pores and throats and identifying their deformation history, as the path followed by these elements is random and can have several unpredictable outcomes.
- The mixing of fluid elements with various deformation histories in the individual pores and throats. As a result, the viscosity is not a well-defined property of the fluid in the pores and throats.
- The change of viscosity along the streamline since the deformation history is continually changing over the path of each fluid element

Eventough we encounters so many problems, but network modelling is still the simplest approach that simulates the flow in real situation. Thus, most of the network models are relying on the assumption made, hence avoiding the important physical process that has strong influence on the flow.

Power-Law Flow in Porous Medium

For a porous medium, the laminar flow of Newtonian Fluid is given by Darcy's law:

$$\frac{\Delta P}{L} = \frac{\mu q}{K} \quad \text{(a)}$$

To describe the flow of polymer solutions their non-Newtonian behaviour must be taken into account. To allow for the shear-thinning characteristics an equation must be derived which adapts Darcy's law to the power law flow. The derivation of this equation is based on the flow analogy in porous medium and in a cylindrical tube or capillary which involves the following step;

a) The Newtonian flow in a porous labyrinth is compared with that in a capillary (Poiseulle's law) using Kozeny's concept which relates pore geometry to permability/porosity.

b) Then an expression is given which extends Poiseulle's Law to the laminar flow of power-law fluids;

c) Finally the Kozeny's concept is introduce to convert the modified Poiseulle's equation into modified Darcy's equation.

The laminar flow of a Newtonian fluidin a capillary is expressed by the Poiseulle's law as;

$$\bar{v} = \frac{R^2}{8\mu} \cdot \frac{\Delta P}{L} \quad \text{(b)}$$

In Kozeny's concept, a porous medium is reduced to a bundle of straight capillaries whose dimensions are characterised by 2 parameter which; the average pore radius, r and the tortuosity factor Le/L. Introduction of tortuosity factor has a dual effect;

a) On shear rate because the linear flow rate in the capillary $\bar{v}$ is to be converted into superficial flow rate u in the porous medium;

$$\bar{v} = \frac{u}{\omega} \cdot \frac{L_e}{L} \quad \text{(c)}$$

b) On shear stress because the effective pressure gradient becomes ΔP/Le instead of ΔP/L:

$$\frac{\Delta P}{L_e} = \frac{\Delta P}{L} \cdot \frac{L}{L_e} \text{(d)}$$

Introducing (c) and (d) into equation (b) and equating R by r we get;

$$u = \frac{\omega r^2}{8\mu} \left(\frac{L}{L_e}\right)^2 \frac{\Delta P}{L} \text{(e)}$$

Comparing (e) and (a) result in;

$$r \cdot \frac{L}{L_e} = \frac{8k_2^{\frac{1}{2}}}{\omega} \qquad \text{(f)}$$

Which expression relates the microscopic parameters r and Le/L to the macroscopic parameters k and ω. As mention before, the flow of power-law fluids is characterised by the two parameters K and n. They replaced the single viscosity constant in Newtonian flow. For power-law flow in a capillary, the flow rate is given by Rabinowitsch equation:

$$\bar{v} = \frac{n}{3n+1} R^{\frac{n+1}{n}} \left(\frac{\Delta P}{2KL}\right)^{\frac{1}{n}} \text{(g)}$$

Which for n=1 with K=μ. Reduces to equation (a)

Applying the same approach to Kozeny's capillary model, we get;

$$u = \frac{\omega n}{3n+1} \left(\frac{8k}{\omega}\right) \left(r \cdot \frac{L}{L_e}\right)^{\frac{n+1}{2n}} \left(\frac{\Delta P}{2KL}\right)^{\frac{1}{n}} \text{(h)}$$

Which for n=1 and K=μ reduces to equation (e). Substitution of (f) into (h) finally gives;

$$u = \frac{\omega n}{3n+1}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}}(2\kappa)^{-1}\left(\frac{\Delta P}{L}\right)^{\frac{1}{n}} \quad \text{(i)}$$

Which u=Q/A, changing the equation

$$Q = \frac{A\omega n}{3n+1}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}}(2\kappa)^{-1}\left(\frac{\Delta P}{L}\right)^{\frac{1}{n}} \text{....(j)}$$

For this paper we will be focusing on this equation as we will developed a relation between Q and K and n from the experiment.

CHAPTER 3

METHADOLOGY

3.1 Project Identification

Test that will be conducted for this project;

1. Rheological Properties: is the study of flow of matter primarily in liquid states. This applies to the non-Newtonian fluid that will be used in the experiment: oil. The equipment used to measure the rheological properties of the fluid is viscometer. This is a 6 speed viscometer. The speed can be adjusted by changing the Dial knob at the side of the equipment. This equipment can be used to measure;

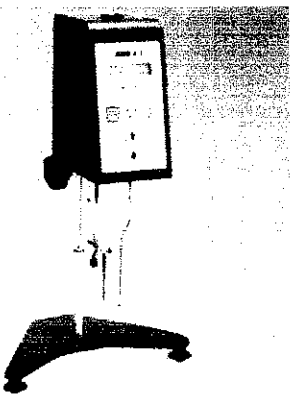


Figure3.1

- Plastic Viscosity (cP) – PV is the slope of sheer stress/shear rate. It represents the viscosity of oil. Low PV means the oil used is light. High PV means the oil is too viscous; Calculated from 600rpm-300rpm dial reading

- Apparent Viscosity (cP) - Rheological property calculated from viscometer reading also known as AV. It is expressed in centipoises.

$$AV_{cP} = \frac{x}{2}$$

- AV = Apparent viscosity
- cP = centipoises
- 1 Centipoise = One hundredth of a poise
- x = The 600_{rpm} reading from a viscometer
- rpm = Revolutions per minute

- Yield Point (lbs/100 ft²) - YP is Stress at which a material deforms plastically. Calculated from PV-300rpm dial reading

- Gel Strength (lbs/100 ft²)/10s@10m - Shear stress measured at low shear rate after the fluid sample has set quiescently for a period of

time. Normally, we take 10seconds & 10minutes gel strength, but some of might take up to 30 minutes gel strength. This property helps measuring thixotropic properties of the fluid.

2. After determining the basic rheological properties of the non-Newtonian fluid, we proceed with;

I. Displacement test or polymer core flooding experiment using RPS 830 equipment

Before we proceed with the experiment, first we must clean the core;

3.2 Core Cleaning

Before displacement test can be carried out to measure relative permeability and the oil recovery, it is a must to clean and saturate the core properly to ensure each runs are not affected by any impurities inside the core sample. To restore the native state of the core sample, the core must be clean thoroughly.

Chemicals and Apparatus

Dean-Stark Soxhlet Extractor, Toluene

Procedure:

- *The Soxhlet distillation extraction method is used to dissolve and extract oil and brine from rock core sample by using solvents.*
- *The cleanliness of the sample is determined from the colour of the solvent that siphons periodically from the extractor which must be clear. The samples are placed in the extractor and cleaned by refluxing solvent.*
- *The solvent is heated and vaporized in boiling flasks and cooled at the top by condenser. The cooled solvent liquid falls into the sample chamber. The cleaned solvent fills the chamber and soaks the core sample. When the chamber is full, the dirty solvent which was*

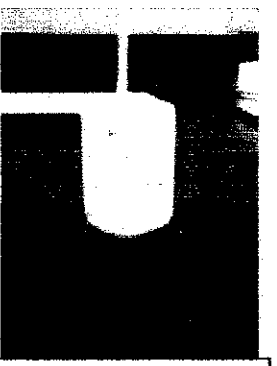


Figure 3.2: Core Sample

used to clean the core siphons back into the boiling flask and is redistilled again.

3.3 Dry Core Properties

Chemicals and Apparatus

Oven, Helium Porosimeter

Nitrogen gas

Procedure:

- Before the core can be saturated, measurements of air porosity and permeability must be done.
- After the cleaning process, the core samples are put into oven to dry any residues of toluene which might be still entrapped in the pore spaces.
- Using Porosimeter, nitrogen gas is filled into the core chamber to completely saturate the sample.
- Using suitable confined pressure and setting up the pressure steps for reading purposes, stabilize air porosity and absolute permeability values are obtained.

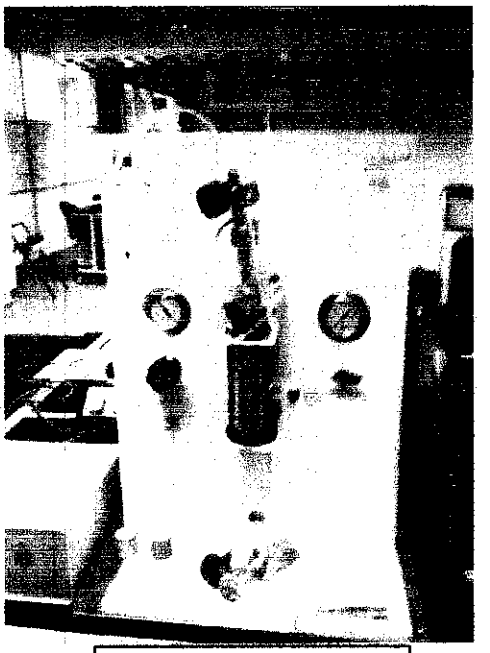


Figure 3.3: Porosimeter

3.4 Polymer Flooding

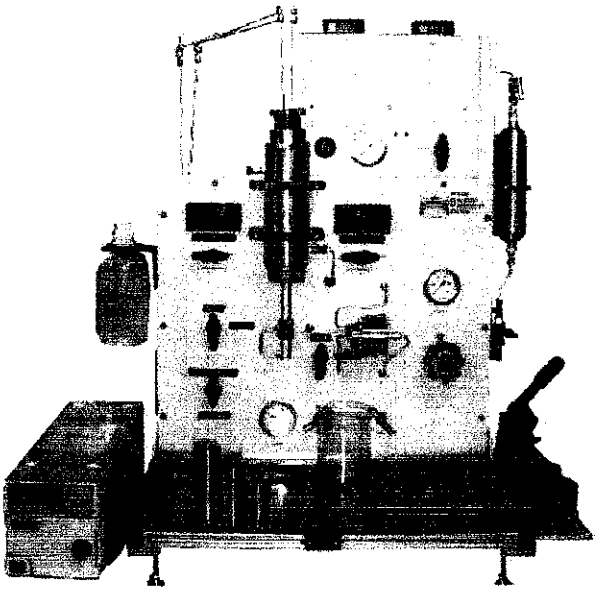


Figure 3.3: BPS 805

The core sample must be properly saturated with the desired fluids and ensure duration of aging of the fluid to properly wet the core is sufficient.

Chemicals and Apparatus

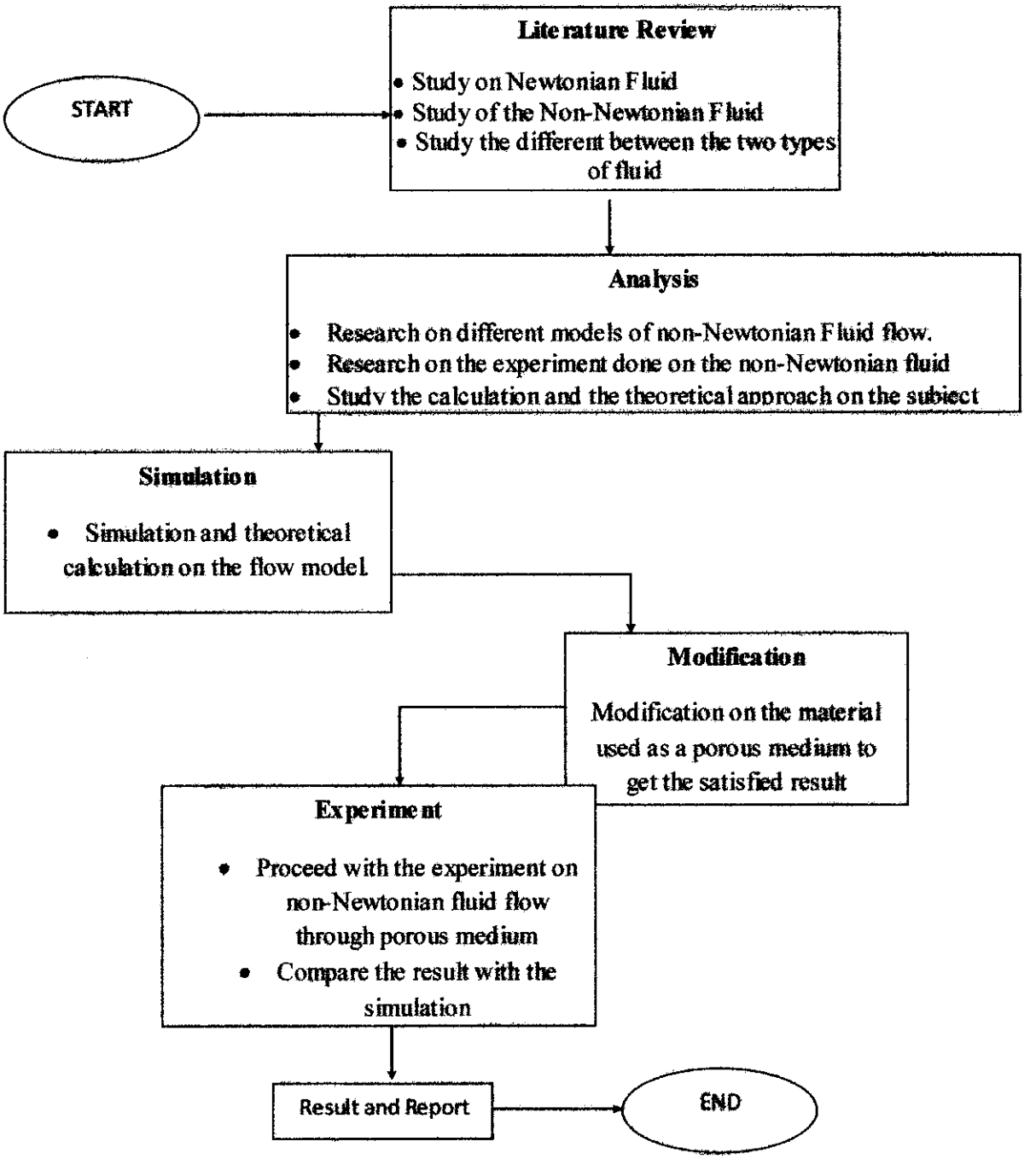
Bench Permeability System

Non-Newtonian Fluid Sample

Procedure:

- Basically, the core sample will be saturated by using the same polymer that will be injected inside it. The core will be saturated for at least 6 hours to ensure the fluid is properly wet the core.
- Then, the core will be flooded with the polymer sample. The injection pressure is set at 1000 psi. The 1st flow is set at 2cc/min and is recorded after the differential pressure is stabilised.
- After all the differential for each flow rate is recorded, we extract all the previous sample from the core and inject another sample.

3.5 Project Flow



CHAPTER 4

Data and Discussion

Core Name	K-4
Porosity (%)	18.365
Permeability (air,mD)	102.676355
Permeability (infinite,mD)	79.4838491
Diameter, cm	3.802
Length, cm	7.524
Volume Bulk, cc	83.6775526
Volume Pore, cc	15.3674193
Volume Grain, cc	68.3101334
Grain Density, g/cc	2.55249088
Bulk Density, g/cc	2.08372481
Dry Weight, gm	174.361

Table 4.1: Properties of The Core Used

Above is the porosity and permeability of the core measured by using the Porosimeter. We use the same core for each run to maintain the porosity and permeability data. The only thing that will change while running the core flooding process is the pressure difference ΔP, and the type of fluid use. The pressure will vary from 25psi-100psi and for each of the pressure change; the flow rate will be recorded. From the experiments done, the results are,

SAMPLE 1; 0.1 ppg Xanthan Gum + 1% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/ft)	Log Q	Log ΔP/L (psi/ft)
2	10.2	0.0732	0.247	41.31227217	0.30103	1.616079082
2.5	14.3	0.0732	0.247	57.9181855	0.39794	1.762814948
3	17.3	0.0732	0.247	70.06885379	0.477121	1.845525013
3.5	19.8	0.0732	0.247	80.19441069	0.544068	1.9041441
4	21.8	0.0732	0.247	88.29485622	0.60206	1.945935404
4.5	24.8	0.0732	0.247	100.4455245	0.653213	2.001930591
5	27.5	0.0732	0.247	111.381126	0.69897	2.046811604
5.5	30.8	0.0732	0.247	124.7468611	0.740363	2.096029627
6	33.5	0.0732	0.247	135.6824625	0.778151	2.132523717
6.5	36.9	0.0732	0.247	149.4532199	0.812913	2.174505276

Table 4.2: Flow of Sample 1 through Porous Medium

SAMPLE 2: 0.1 ppg Xanthan Gum + 5% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/ft)	Log Q	Log ΔP/L (psi/ft)
2	64.3	0.0732	0.247	260.4293236	0.30103	2.415689883
2.5	72.1	0.0732	0.247	292.0210612	0.39794	2.465414175
3	92.4	0.0732	0.247	374.2405832	0.477121	2.573150881
3.5	130.2	0.0732	0.247	527.3390036	0.544068	2.722089894
4	165.8	0.0732	0.247	671.526934	0.60206	2.827063436
4.5	187.3	0.0732	0.247	758.6067234	0.653213	2.880016687
5	199.8	0.0732	0.247	809.2345079	0.69897	2.908074394
5.5	213.5	0.0732	0.247	864.7225597	0.740363	2.936876789
6	234.7	0.0732	0.247	950.5872823	0.778151	2.977992
6.5	245	0.0732	0.247	992.3045768	0.812913	2.996644994

Table 4.3: Flow of Sample 2 through Porous Medium

SAMPLE 3: 0.1 ppg Xanthan Gum + 10% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/ft)	Log Q	Log ΔP/L (psi/ft)
2	98.3	0.0732	0.247	398.1368975	0.30103	2.600032428
2.5	124.3	0.0732	0.247	503.4426893	0.39794	2.701950039
3	168.3	0.0732	0.247	681.6524909	0.477121	2.833563026
3.5	205.4	0.0732	0.247	831.9157554	0.544068	2.920079349
4	245	0.0732	0.247	992.3045768	0.60206	2.996644994

Table 4.4: Flow of Sample 3 through Porous Medium

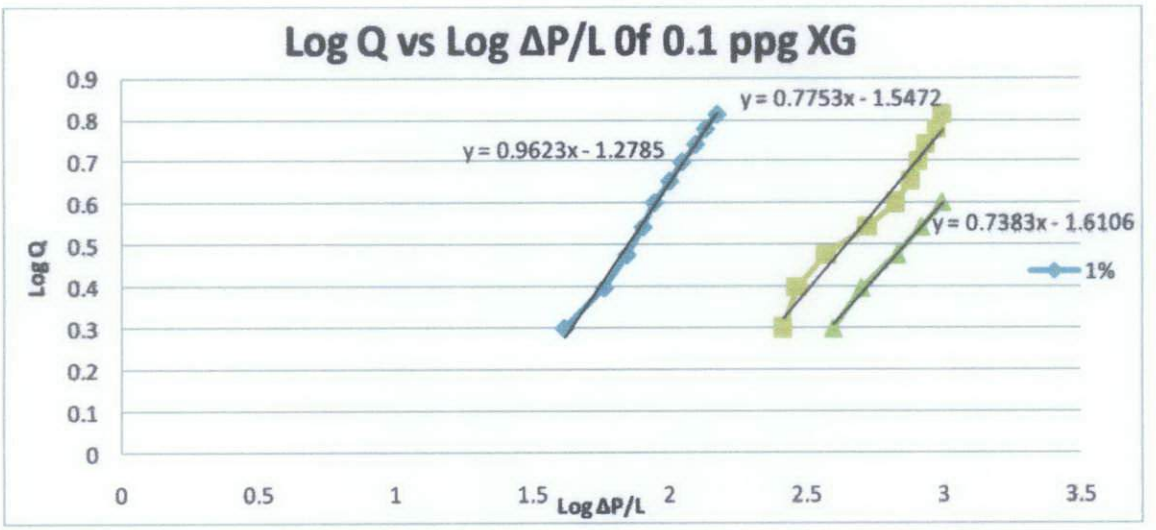


Figure 4.5: Flow of 0.1 Xanthan Gum With Different NaCl Concentration in Porous Medium.

SAMPLE 4: 0.3 ppg Xanthan Gum 1% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/m)	Log Q	Log ΔP/L (psi/m)
2	40.2	0.075	0.247	162.7530364	0.30103	2.2115291
2.5	56.4	0.075	0.247	228.340081	0.39794	2.358582151
3	69.1	0.075	0.247	279.757085	0.47712	2.446781094
3.5	76.3	0.075	0.247	308.9068826	0.54407	2.489827585
4	83.6	0.075	0.247	338.4615385	0.60206	2.529509324
4.5	90.9	0.075	0.247	368.0161943	0.65321	2.56586693
5	98.9	0.075	0.247	400.4048583	0.69897	2.602499338
5.5	107.9	0.075	0.247	436.8421053	0.74036	2.640324491
6	116.3	0.075	0.247	470.8502024	0.77815	2.672882761
6.5	124.9	0.075	0.247	505.6680162	0.81291	2.703865485

Table 4.6: Flow of Sample 4 through Porous Medium

SAMPLE 5: 0.3ppg Xanthan Gum 5% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/m)	Log Q	Log ΔP/L (psi/m)
2	112.4	0.075	0.247	455.2450385	0.301029996	2.658
2.5	157.3	0.075	0.247	637.1000405	0.397940009	2.804
3	182.8	0.075	0.247	740.3807209	0.477121255	2.869
3.5	208.3	0.075	0.247	843.6614014	0.544068044	2.926
4	225.4	0.075	0.247	912.9202106	0.602059991	2.960
4.5	245	0.075	0.247	992.3045768	0.653212514	2.997

Table 4.7: Flow of Sample 5 through Porous Medium

SAMPLE 6: 0.3ppg Xanthan Gum 10% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/ft)	Log Q	Log ΔP/L (psi/ft)
2	170.3	0.075	0.247	689.7529364	0.301029996	2.839
2.5	211.3	0.075	0.247	855.8120697	0.397940009	2.932
3	245	0.075	0.247	992.3045768	0.477121255	2.997
3.5	245	0.075	0.247	992.3045768	0.544068044	2.997
4	245	0.075	0.247	992.3045768	0.602059991	2.997

Table 4.8: Flow of Sample 6 Through Porous Medium

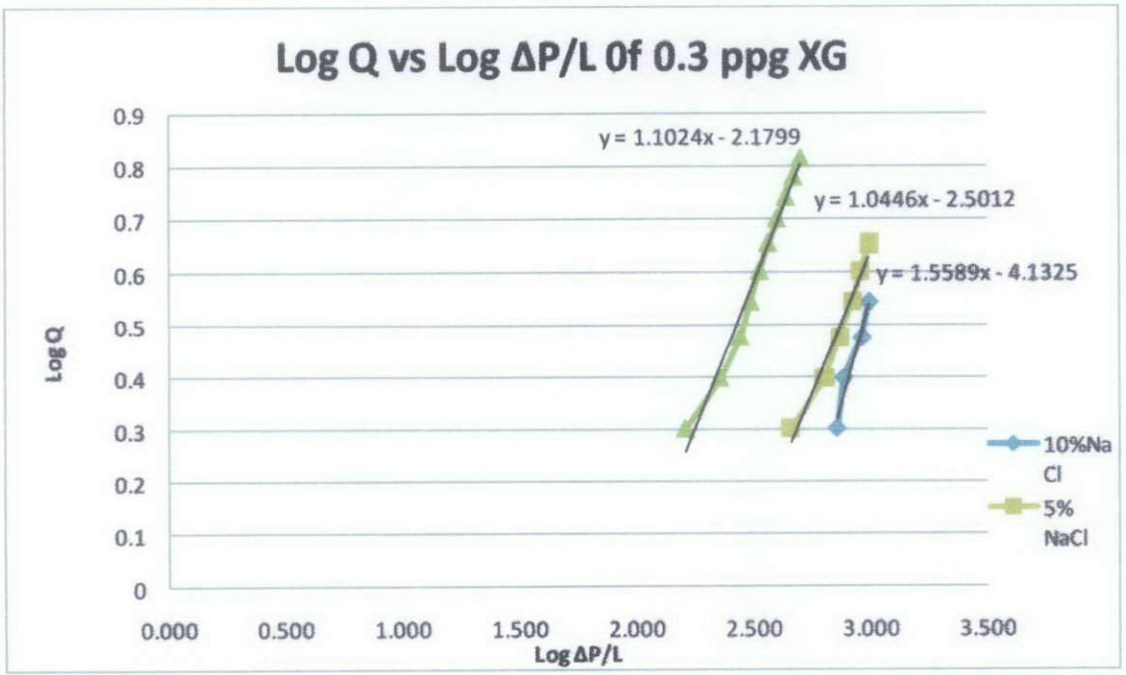


Figure 4.9: Flow of 0.3 Xanthan Gum With Different NaCl Concentration in Porous Medium.

SAMPLE 7: 0.5ppg Xanthan Gum 1% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/ft)	Log Q	Log ΔP/L (psi/ft)
2	145.3	0.075	0.247	588.4973674	0.30103	2.770
2.5	178.4	0.075	0.247	722.5597408	0.39794	2.859
3	210.4	0.075	0.247	852.1668692	0.477121	2.931
3.5	238.5	0.075	0.247	965.9781288	0.544068	2.985
4	245	0.075	0.247	992.3045768	0.60206	2.997

Table 4.10: Flow of Sample 7 Through Porous Medium

SAMPLE 8: 0.5ppg Xanthan Gum 5% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/ft)	Log Q	Log ΔP/L (psi/ft)
2	182.7	0.075	0.247	739.9756987	0.30103	2.869
2.5	218.3	0.075	0.247	884.163629	0.39794	2.947
3	238.8	0.075	0.247	967.1931956	0.477121	2.986
3.5	245	0.075	0.247	992.3045768	0.544068	2.997

Table 4.11: Flow of Sample 8 Through Porous Medium

SAMPLE 9: 0.5ppg Xanthan Gum 10% NaCl

Q (cc/2min)	ΔP (psig)	L (m)	L(ft)	ΔP/L (psi/m)	Log Q	Log ΔP/L (psi/m)
2	212.3	0.075	0.247	859.8622924	0.30103	2.934
2.5	238.3	0.075	0.247	965.1680842	0.39794	2.985
3	245	0.075	0.247	992.3045768	0.477121	2.997

Table 4.12: Flow of Sample 9 Through Porous Medium

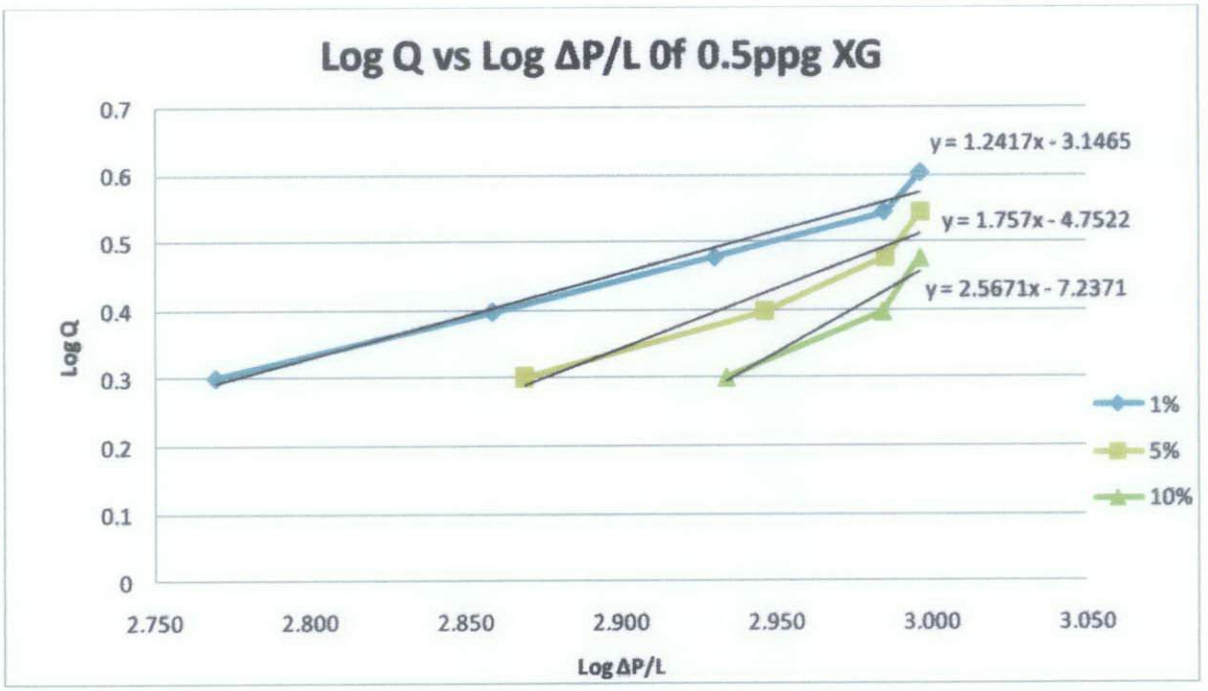


Figure 4.13: Flow of 0.5 Xanthan Gum With Different NaCl Concentration in Porous Medium.

4.1 Calculation Procedure

The graph will intercept at the y-axis. The slope of the graph give us 1/n value. Which will later help us determine the consistenscy index value.

$$Q = \frac{\omega n}{3n+1}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}}(2\kappa)^{-1}\left(\frac{\Delta P}{L}\right)^{\frac{1}{n}} \quad \text{(j)}$$

Transpose the above equation into the log form, we get

$$Q = \frac{A\omega n}{3n+1}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}}(2\kappa)^{-1}\left(\frac{\Delta P}{L}\right)^{\frac{1}{n}}$$

$$\frac{A\omega n}{3n+1}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}}(2\kappa)^{-1} = C \ldots\ldots \text{(k)}$$

So, we get;

$$\text{Log Q} = \text{Log C} + \frac{1}{n} Log\left(\frac{\Delta P}{L}\right) \text{.....(L)}$$

$$y = mx + c$$

So from the equation, we produce the following graph to show the relationship between Log Q and $Log\left(\frac{\Delta P}{L}\right)$. The slope of the graph shows the value of $\frac{1}{n}$ and the interception between the relationship and the y-axis shows the value of Log C. From the Log C value we may able to find the value of the Consistency index, K. If the n=1, then the sample tested is the Newtonian liquid, if not, it is a non-Newtonian Fluid. From the equation, the n and K value for the non-Newtonian fluid use in the experiment are;

As we know the property of the core has been determined by using the Porosimeter Equipment, substituting the value inside the equation, and from the graph we can determine the value of n and K. The value of n which can be determined from the slop of the graph and the K value are;

Sample 1;

$Log\ C = -1.2785$

So, $C = Log^{-1} - 1.2785$

$C = 0.0526623$

$n = \frac{1}{0.9623} = 1.03918$

To find the value of consistency index, K rearrange the equation, we get;

$$\frac{A\omega n}{3n+1}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}} (2\kappa)^{-1} = 0.05266$$

$$\frac{A\omega n}{2(0.1579n + 0.05266)}\left(\frac{8k}{\omega}\right)^{\frac{n+1}{2n}} = \kappa$$

Substituting the value of k, ω, A and n, we get;

$$\frac{0.01208(18.365)(1.03918)}{2[0.1579(1.03918) + 0.05266]}\left(\frac{8(102.6764)}{18.365}\right)^{\frac{1.0392+1}{2(1.0392)}} = \kappa$$

$$\kappa = 22.149$$

Hence, the value of n and K value of each sample are;

No	Fluid Sample	Log C	1/n	n	K	% NaCl
1	0.1 ppg XG + 1% NaCl	-1.2785	0.9623	1.03918	22.14934	1%
2	0.1 ppg XG + 5% NaCl	-1.5472	0.7753	1.28982	30.25002	5%
3	0.1 ppg XG + 10% NaCl	-1.6016	0.7383	1.35446	32.27505	10%
4	0.3ppg XG +1% NaCl	-2.1799	1.1024	0.90711	222.4818	1%
5	0.3ppg XG +5% NaCl	-2.5012	1.044	0.95785	423.2763	5%
6	0.3ppg XG +10% NaCl	-2.8491	1.723	0.58038	2934.239	10%
7	0.5ppg XG +1% NaCl	-3.1465	1.2417	0.805348	2596.312	1%
8	0.5ppg XG +5% NaCl	-4.7522	1.757	0.569152	248622.5	5%
9	0.5ppg XG +10% NaCl	-7.2371	2.5671	0.389545	3.02E+08	10%

Table 4.14: Value of n and K for each Sample

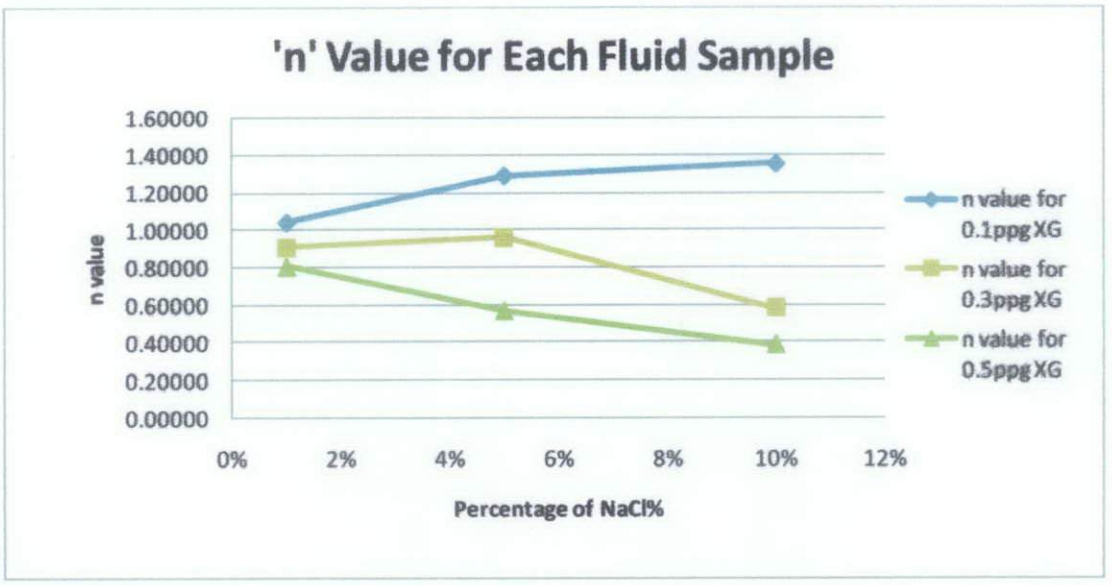


Figure 4.15: Value of n vs Concentration of NaCl for Each Fluid Sample

4.2 Analysis of n and K

For fluid sample 1, 4 and 7 we can see that the increment in the concentration of Xanthan Gum inside the fluid sample cause the pressure different needed to flow the fluid through the core sample increase. This may cause by the high flow resistance of the Xanthan Gum polymer solutions in porous media. The increasing number of solids inside the polymer may cause the core to plug and higher differential pressure needed to flush the clogged solids inside the core. Hence, the more viscous the solution, the higher the resistance of the fluid to flow through the core.

For fluid sample 2, 3,5,6,8, and 9 the percentage of NaCl for each of the sample is increased by 5% to 10%. Each of the samples shows exhibit different n and K value at each increment. For fluid samples with 0.1 ppg of Xanthan Gum, they exhibit a shear thickening properties. The n value calculated from the graph plotted is more than 1. For power law fluid, if the n value is more than 1, than the fluid is a shear thickening fluid. This means that the viscosity of the fluid increases with the rate of shear applied on the fluid. This is due to when closely packed particles are combined with enough liquid to fill the gaps between them. For fluid sample with 0.2 ppg Xanthan Gum and 0.5 ppg Xanthan Gum, the result of experiment shows irregularities. This is because as expected, the n value should be increased or decrease but the

result shows otherwise. This may caused by the limitation on the equipment used which is the Bench Top Permeability System (BPS-805). The equipment limits the pressure at 245psi. So the viscous the liquid, the higher the differential pressure needed to flow the fluid samples through the core.

Because of that, for viscous fluid samples such as 0.5ppg Xanthan Gum + 10% NaCl needs higher pressure difference to flow but since the highest Pressure that the equipment can reach is 245 psi, so the pressure cannot be determine. But from the table above, we can see that for the fluid samples with 0.3 ppg Xanthan Gum, most of the fluid exhibit shear thinning properties or pseudoplastic properties since the n value calculated for each of sample with different salt (NaCl) percentage is lower than 1, which means that the viscosity of the fluid decreases with increasing rate of shear stress.

For fluid samples with 0.5 ppg Xanthan Gum, the same situation occurs. All of the fluid exhibit pseudoplastic properties of power law fluid with n lower than 1. But the consistency index value for this sample is very high, showing that the resistance offered by the fluid to continuous deformation when subjected to shear stress is very high.

As we can see, from fluid sample 1 to fluid sample 9, the increasing concentration of Xanthan Gum and salt content (NaCl) affected the consistency index, K of the fluid, the more viscous the fluid, the more resistance offered by it to continuous deformation when subjected to shear stress. Eventhough the results obtain is not as expected, but the study done on this matter has improve the knowledge on the behaviour of the fluid

CHAPTER 5 CONCLUSIONS AND RECOMMEDATIONS

5.1 CONCLUSION

I. At the end of the project, the modified Darcy equation used to determine the flow behaviour of the project has achieved mere successful results.
II. The improved equation for laminar flow of shear thinning fluids in porous medium by adapting Darcy's Law to power-law flow has been used and helps determine the shear thinning characteristic of the fluid samples in core flow.
III. Flow of a power-law fluid through core sample cause increment in pressure difference as the size of the polymer molecules and increase in number of solids (Salt) inside the polymer increase
IV. Eventhough there has been irregularities in the results, which can be neglected due to limitation of the equipment used.

5.2 RECOMMENDATION

The time constraint for student upon completing the project is significant. As a student, more time needed since there are lots of projects for final year student. Furthermore, the course coordinator should inform any change quickly so the student can prepare for any change in a nick of time.

The equipment use for this for experiments should be calibrate and in this case, a different equipment with better capabilities should be used to cater the experiments requirement. Since the equipment is not available upon the time for the student to use, the results obtain is inaccurate and the students needs to retest the sample for many times.

CHAPTER 6

REFFERENCES

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PROJECT ACTIVITIES		W 1	W 2	W 3	W 4	W 5	W 6	MID-SEMESTER BREAK	W7	W8	W9	W10	W11	W12	W13	W14
Receive the FYP title																
Discuss and update progress with supervisor about the project.																
Literature Review	Gather info from journal, books etc															
	Research on Non-Newtonian Fluid															
Preliminary Report	preparation on report															
	Submission to supervisor															
Develop Research	Simulate the flow of non-newtonian fluid in porous medium by calculation and research															
	Proceed with the experiment on flow of non-Newtonian fluid through porous medium															
Progress Report.	preparation on report															

	Submission to supervisor																	
Seminar																		
Develop Research	Research on non-Netonian fluid flow behaviour in porous medium																	
	Comparing result obtained from the lab and the theorotical result																	
Submission of Interim	preparation on report																	
Report Final Draft	Submission to supervisor																	
Oral presentation																		